VOWEL-SOUND.

Thesis presented to the University of London, by R. J. LLOYD, M.A., Candidate for the degree of Doctor of Literature, 1890.

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SOME RESEARCHES INTO THE NATURE OF

VOWEL-SOUND.

The treatise on "Phonetic Attraction," which I had the honour of submitting to the University two years ago, was the firstfruit of an investigation into the laws of form, and of the rise and change of forms, in language, which I have continued to prosecute until the present time. That treatise had been essentially prompted by a dissatisfaction with the crude system of doctrine which passes at present under the name of Phonetics, and which attempts to settle everything in language and in the history of language upon merely mechanical grounds. Encouraged by the conditional approval which was then accorded to me by the Examiners, I next applied myself to a minute critical examination of the science of Phonetics, as at present taught in England, and came to the conclusion that it was radically defective, even from its own mechanical point of view. I therefore proceeded to devote myself to a series of further enquiries and experiments whose aim it has been to re-construct Phonetics as a physical science upon new and sounder bases. I need hardly say that I am still a long way from the completion of this task. But I have perhaps gone far enough to justify me in reporting to the University, in the form of a Thesis, the chief results which I believe to have been already attained.

The prime question in every system of Bhonetics is that relating to the nature of vowels. What is the difference between the vowels and the other elements of speech? What again are the essential differences of the vowels between each other? Contemporary English phoneticians generally answer these questions by saying that the difference lies in the method of their articulation: and substantially identical answers are given by some of the most eminent Continental investigators, such as Sievers and Storm. These all employ for the purposes of phonetic discourse and discussion a system of classification, nomenclature, and conventional signs, which with slight modifications is the Visible Speech alphabet, invented some three or four and twenty years ago by the eminent elocutionist, A. M. Bell. In this system every vowel has a name, and also a symbol, which embodies in itself an indication and rude instruction how the vowel is to be articulated.

But this system is not accepted by all Continental phoneticians. Vietor, Trautmann, Winteler, and other eminent writers, either discard it absolutely or use other modes of classification and nomenclature by preference. A similarity of principle underlies all these other systems: they all classify the vowel according to its sound and not according to its articulation. And certainly, if it is equally possible, it is far more natural to do so. If we were classifying colours or smells we should arrange them according to their shade or their aroma, not according to the shape of the plant or flower from which they happened to proceed. So also it seems at first sight a strange sort of *ὕστερον πρότερον* to name and classify vowels according to the shape of the cavity from which they proceed, rather than according to their heard quality and proved acoustic affinities.

But it is not really quite so strange as it looks. The quality of a vowel depends upon, and is in fact created by, the shape of the cavity through which it comes. And in the existing state of our resources it has been much easier to indicate in words the various shades of difference in the shape of articulate configurations than to give names which would call up instantly and unmistakeably certain definite shades of sound. For this reason the science of speech-sounds, as such, continues to be in a very backward condition, and is in fact largely superseded and hidden by the science of articulations, which in England at any rate monopolizes the title of Phonetics.

It is evident, however, that such a state of things can only be temporary, that in fact we shall never continue to classify sounds according to the accidents of their origin when once we are able to arrange them after the essentials of their nature. Not indeed that we should slacken our study of articulations. Quite the reverse. But we ought to know why certain articulations produce certain sounds, and what is the intimate acoustic nature of the sounds thus produced. When that is done we shall certainly learn first to know the sounds *per se*, and then to know the reasons why certain articulations produce them. Until then we shall always be in danger of viewing the subject in an inverted perspective, hardly seeing that which ought to be the chief object of our view. Phonetics is defined to be the "science of speech-*sounds*." Now the first thing we want to know about a sound is its acoustic nature; our interest in its mode of production is only of a secondary kind.

It follows then that in the phonetic science of the future speech-sounds will certainly be classed not according to their articulation, but according to their acoustic essence; and the study of articulations will be the first handmaid of Phonetics, but will stand no risk of being mistaken, as it now is, for Phonetics itself. This being so, it seems clear that the path of greatest usefulness at present in phonetic investigation is to enquire further into the acoustic nature of speech-sounds, and especially of vowels. This has been done already to a certain extent, but not to anything like a sufficient degree. Nearly every phonetician of the acoustic school has his own scheme or diagram of classification, wherein the vowels are duly arranged in an order which seems suitably to represent their relative affinities of sound: and some physicists also, notably Willis and Helmholtz, have made partially successful attempts to analyze the different vowels into their acoustic elements, and also to construct artificial vowels. But the latter attempt seems only to have succeeded well with the graver vowels, such as *u* and *o*: the attempt to produce *i* (English *ee*) was a failure altogether.

Under these circumstances it seemed desirable to investigate the vowels afresh, beginning if possible from the acute or *i* end of the scale, where previous investigation had left fewer tangible traces. The mere discrimination of certain standard vowels by ear is palpably insufficient for scientific purposes. Such standards must necessarily be wanting in fixity, in definiteness, in communicability; there is no possible security that everybody would always use them in the same exact sense. We must get down to some objective and permanent criterion of the differences of vowel-sounds before we can even begin to talk quite scientifically about them.

Such an attempt had been not long ago made by one of the authorities already mentioned, Professor Trautmann of Bonn. That scholar, after a very large and laborious experimentation, chiefly with tuning forks, arrived at the conclusion that each vowel-configuration has a pitch of its own, which is identical, for that vowel, in all persons, young or old, large or small, male or female. In whisper, this note is heard almost pure; in loud speech it is crossed by the strong vibrations issuing from the glottis or vocal chords. But in both cases the heard sound possesses the same vowel quality, and in both cases it is conferred, says he, by the concomitance of the tones of one certain definite pitch which are created by the resonance of the given vowel-configuration. He recommends the study of these resonances in the *whispered* vowels, because the other elements are therein feebler; and the aim of his experiments with the tuning-forks is then to discover what note each vowel-configuration will most readily and loudly resound to. This note he takes to be identical in pitch with the resonance which by its added presence creates the vowel, and he considers that by these means he has determined the absolute pitch of this resonance for every vowel.

After carefully examining these doctrines, I found myself unable to subscribe to them. They seemed indeed to me to be based upon a misapprehension of some of Helmholtz's teaching, and to run counter to most of his facts. I began an independent investigation of my own, and the results thereof have appeared from time to time in a series of articles entitled "*Speech Sounds: their Nature and Causation,*" which I am contributing to the specialist organ, the *Phonetische Studien,* edited by Professor Vietor of Marburg. Two articles of that series which have already appeared, and one which is in the press, accompany this Thesis. They lead up to, but do not contain, that general theory of vowel-sound which it is my chief object to unfold in the present discourse. They will therefore need to be frequently referred to, and reference will be most conveniently made to the *sections* into which they are divided. The considerations which induced me to reject Professor Trautmann's doctrine of absolute single pitch will be found chiefly in § *3* and § *9;* they will also partly appear in the further portion of this paper.

But I found in Helmholtz (Ellis' edition, London, 1885, p. 107), a hint which seemed to be of a fruitful nature. "When a bottle," says he, "with a long narrow neck, is used as a resonance chamber, two simple tones are readily discovered, of which one can be regarded as the proper tone of the *belly*, and the other as that of the *neck* of the bottle." My previous study of articulations led me at once to recognise that the principle here announced was probably applicable to certain vowel articulations, and in fact to those of the very vowels which seemed to stand most in need of further physical investigation. What we really do when we articulate an *i* vowel is to create a *neck,* of a certain proportionate size, to the vocal cavity. The tongue is so presented to the opposing surface of the hard palate as to leave a narrow channel between them, which is for the time being a veritable neck to the inner cavity. It is true that this inner cavity is of a shape very much more irregular than that of a bottle; but a suggestive observation of Liscovius, recorded by Lord Rayleigh in his "*Theory of Sound,*" (Ed. 1, Vol. II., p. 173) led me to infer that these irregularities had little, if any, influence upon the pitch of resonance produced.

I also obtained from the same source a knowledge of some observations by Sondhauss, without which I should have been unable to make a very necessary correction to the dictum of Helmholtz which is quoted above. Helmholtz is perfectly right in saying that a long-necked bottle has two resonances—a few experiments with bottles made that clear immediately. And he is also right in saying that one of these resonances is the resonance of the neck; but he is wrong in saying that the other is that of the belly of the bottle. It is really that of the whole bottle, neck and all. This fact is established by the above-named observations of Sondhauss, who not only noticed the existence of these vibrations, but developed by a series of careful experiments a mathematical expression for their pitch-number, viz.:—

$$N = 46705 \frac{\sigma^{\frac{1}{2}}}{L^{\frac{1}{2}} \; S^{\frac{1}{2}}}$$

where N is the speed of vibration, expressed in complete (or double) excursions per second, σ is the area of the orifice, L the length of the neck, and S the volume of the bottle, all in millimetres, square, lineal and cubic respectively. The note thus discovered is the deepest or fundamental resonance of the bottle, and it is also undoubtedly that second resonance which Helmholtz talks about in the passage quoted but does not quite correctly identify.

For Helmholtz himself gives formulæ for calculating the resonance of a cavity like the belly of a bottle, and I found on evoking the resonance of various bottles that the deeper of the two resonances did not answer to this calculation; but it did answer very exactly to Sondhauss' formula, which gives us the resonance of the whole bottle, neck included. The formula itself shows that this is the case: for N alters with every variation either in the length or thickness of the neck; whilst if this note were really only the resonance of the belly of the bottle, it would remain always the same irrespective of any and every alteration in the neck.

I had thus arrived at the conviction that the acuter vowels, by which I mean those resembling *i* and *e* (the vowels of English *feet* and *fate*), must have two resonances; and that if their configurations could be accurately measured these resonances could be determined with mathematical precision. The importance of this discovery arose from the fact that, partly from the mixture of the resonances with each other and with foreign elements, and partly from the inability even of a keen and trained ear to distinguish any faint sound from its Octave, or even its Double Octave, it did not seem safe to place any reliance whatever upon the direct observation of these resonances by the ear. Tables of such observations, made by many eminent philosophers, are given by Ellis in his edition of Helmholtz (ed. 2, p. 109) and by Trautmann in his *Sprachlaute* (Leipzig, 1885.) *There is no single sound about which the philosophers do not disagree to the extent of several octaves!*

Such being the case, it seemed highly satisfactory to be at length in possession of means which might be sufficient to determine these troublesome resonances by calculation. Even if the calculation could not be carried out with all the minuteness that might be desired, it would at any rate prevent mistakes of an octave, at once and for ever. But the difficulties of this course were considerable. They did not lie in the calculation itself, but in the measurements which must precede the calculation. These could only be taken approximately at the best; and no ready means of direct verification seemed possible. In this juncture I devised two kinds of apparatus which afforded, though in an indirect manner, the verification here required.

The first apparatus consisted of (1) a bottle, which was chosen because its size seemed to correspond most nearly with the estimated size of the inner cavity of an *i* articulation, and (2) a neck, fitted tightly into the cork of this bottle and made to correspond in a similar way to the tubular portion of an *i* articulation. This apparatus was not at all a model of the whole configuration of *i*: it was much rather, so far as appearances went, a caricature of it. But it was thereby all the better fitted for the purpose in hand. For whilst in the natural configuration it is extremely difficult to say with certainty where the tube ends and the cavity begins, both can be measured in this apparatus with any desired degree of accuracy. And the elimination of every feature of the configuration except its division into a cavity of a certain size and a tube of a certain calibre and length was well fitted to demonstrate whether these were really its only essential features or not.

The next problem was to make this artificial configuration somehow or other into a channel of resonance, like the voice-tunnel of which it is the modified presentment. My first attempt was made with a reed inserted through the cork of the bottle, and sounding into the inner cavity just as the vocal chords sound into the voice-tunnel. But this attempt was a failure, and I have since learned the reason why that was the case. My reed ought not to have been chosen at random, but ought to have been identical in pitch with the lower resonance of the bottle. As it was, it had no manner of adaptability to the task which it had to perform. Resonances are easily and forcibly aroused by tones of their own pitch, or by tones whose pitch is any near multiple or submultiple of their own, but in most other cases they are crossed and quenched rather than stimulated, and this was just what happened in my apparatus. The same thing would happen in ordinary speech if our articulations were not habitually *tuned* to the normal monotone of the glottis, and *retuned* at every inflection of the glottal tone. It is this perpetual tuning process in lively speech which occasions that curious pumping movement of the larynx or Adam's apple, which is so visible in many speakers. But in normal monotone and in whisper I found the larynx to maintain its position of neutrality or rest.

Pending this discovery I followed Professor Trautmann's example, and simplified the problem before me by studying the vowels in their whispered form. The advantage of th was that the powerful tones of the glottis were eliminated from the enquiry, and it was no longer necessary to provide anything in the experimental apparatus to take their place. Not that the glottis is entirely inactive in the production of whisper, but it descends from its sonant into what may be called its sibilant condition,—a state in which the proper vibrations of the chords die down and cease to be audible beside the frictional noise of the air as it hisses or fizzes its way from between the loosely juxtaposed chords. The operation of these glottal noises in animating the resonances of the various whispered vowels seems to be analogous to that of the wind in an organ as it breaks upon the lip of the pipe or pipes whose resonance it is intended to animate. Its power lies in the heterogeneousness of its vibrations.

It is not necessary, in order to arouse the resonance of any given cavity, that the exciting cause should be a strong one, provided only that it is just about a certain pitch and is not too momentary in duration. The miscellaneous hiss of the sibilant or whispering glottis has the same power which is possessed by the broken and fluttering stream of air at the mouth of an organ pipe, to excite the resonance of almost any configuration which may be presented to it. Such is the variety of its vibrations that some at least are always found to minister the requisite stimulas: and thus the same glottal hiss is efficient in arousing the whispered resonance of every vowel configuration.

It was not very hard to imitate this provision in the experimental apparatus. Instead of the reed which had formerly been inserted in the cork, a glass tube was now thrust through, of which the inner end was packed and obstructed with splinters of glass, wood or metal so that, when blown through, it might produce a hiss as strong and various as that of the sibilant glottis itself. To the outer end of this tube another tube of flexible gutta-percha was attached, so that by means of it the hissing-tube might be blown through at the same time that the whole configuration was being held up to the ear of the operator and the issuing sound was being noted. In doing this it was very necessary to avoid pointing the tubular mouth of the configuration directly at the ear: the rushing stream of air beat in that case against the ear and created a number of disturbing noises which prevented the sound issuing from the experimental apparatus from being accurately heard. The best results were obtained when the tubular outlet of the apparatus was presented sideways to the ear.

When this precaution was observed the sounds issuing from the configuration were at once found to bear a strong resemblance to whispered vowels of the *i* class. Slight successive alterations were made in the calibre of the tube (see *Speech Sounds*, Table I.) in order to determine that calibre at which the *i* vowel was produced most perfectly, but not at first with any marked success. There was a point at which the artificial whisper approached to *i*, but after that point was passed it receded from *i* again, so that at no point was a quite satisfactory *i* produced. But there was another point in the progress of alteration where the English short *i* (the vowel of *tin*) was produced in very great perfection. This was therefore the first whispered vowel whose mode of production was successfully copied by this apparatus. It is perfectly distinct from the long *i*, and in my papers on *Speech Sounds* it is distinguished by the symbol i^2.

It then seemed necessary to return to the (long) *i* vowel and investigate the reason why it was not perfectly reproduced. The organic phoneticians had already noticed that the i^2 vowel, as practically known to us, has a tube of comparatively even calibre, whilst the ordinary *i* vowel, on the other hand, has a tube whose calibre is considerably smaller in the middle of its length than it is at either end. They express this difference in their awkward nomenclature by saying that the i^2 vowel is "wide," but the *i* vowel is "narrow." In order to reproduc this feature in the artificial configuration notice was first tak of the exact size of the tube which had caused the vow whisper to approach most nearly to *i*. Another tube was th constructed of very similar size, but tapering, like the natural *i* tube, from both ends towards the middle. When this tube was fitted to the experimental bottle the issuing sound was a decided *i*.

The acoustic effect of such a modification in the tube of the configuration is discussed at length in § *10* of *Speech Sounds*. The conclusion there arrived at is that the effect would be to develop overtones of the Octave and Double-Octave to the tube-resonance, thus brightening that resonance considerably in musical quality. This conclusion quite agrees with the felt difference in brightness or keenness of quality between the English *i* and i^2 (long and short *i*); and so far the results gained agree exactly with the previous observations of the organic phoneticians. But in another respect they afford a very considerable correction of those observations. The organic phoneticians say that this difference in the shape of the tube, and in consequent keenness of quality, is the *only* difference between *i* and i^2. But that is hardly correct; for the tube which produced the best i^2 was found upon accurate measurement to be 50 per cent. larger in volume than that which produced the best *i*. Not only so, but in the progressive alteration of the calibre of the porch the *i* vowel and the i^2 vowel did not shade off into one another directly, but there was a considerable hiatus between them, which was occupied by a vowel-sound of a much less marked and less determinate character than either. Finally, it was found possible by an appropriate modification of the tube to create a keen form of i^2 which was not *i*, and conversely to produce a dull or blunt form of *i* which was not i^2.

It was thus seen, even at this early stage, that a faithful investigation of speech, from the acoustic side, is certain to reflect a strong light upon the circumstances of its organic production: that, in fact, the true way to success in phonetic enquiry, is not to ignore either the organic or the acoustic facts, but to take them all with us and then find out how they quadrate as we go along. Until this is done the whole science of language remains in a perilous and ungainly position, standing always upon one leg, but not knowing which leg to stand on.

And it is not the organic side of Phonetics only which would gain by the general adoption of such a method: for it is clear already, even from these preliminary steps, that the organic facts are just as capable of correcting acoustic theories as *vice versa*. Organic observation of the division of the *i* configuration into a tube and a cavity aroused, for example, the initial suspicion that the acoustic quality of *i* was determined, not by a single resonance, as imagined from merely acoustic investigation, but by two resonances, acting concomitantly. These first experiments at once raised this impression from suspicion to demonstration: and a careful glance at the remaining vowels, of which the details may be seen in *Speech Sounds*, § 4, brought out the fact that in every leading vowel there is a similar sharp division of the configuration into two parts, which points with great probability to the existence of the same doubleness of resonance in all of them. These two portions of the configuration are not always describable as cavity and neck: the outer portion changes greatly in shape and size, and the inner portion not so much, but still considerably, as we descend from *i* and *e*, through *a*, *o*, and *u*, to the graver end of the series. I have ventured to create a general name for each of these divisions, calling the outer one the "*porch*" and the inner one the "*chamber*" of the respective configurations.

This idea of the essential doubleness of the principal vowel resonances is not a new one. It is expressly announced by Bell in his *Visible Speech*, and a method is there given by which the ear is enabled to recognise this doubleness. But no method is given for exactly determining the lower resonance and when he comes to discuss the pitch of vowels it is the upper pitch only which engages his attention. He makes nc attempt, however, to give an *absolute* value to the upper pitc of every vowel, but only to discriminate the order and interv of their musical succession, as observed in himself.

Those phoneticians, on the other hand, who entirely ignore the existence of a second resonance are led almost of necessity to think that the single resonance which they imagine to confer on each vowel its special vowel-timbre has for each vowel a certain definite pitch. There is no way in which single isolated resonances can be imagined strongly to differ except in absolute pitch. But when it has been shewn that the principal vowels all probably possess *two* resonances we are at once delivered from the necessity of any such inference. It at once becomes conceivable that the fundamental cause of any given vowel quality is the *relation* in pitch between the two resonances, irrespective of any narrow limit in absolute pitch.

The latter supposition was already favoured, or to speak more correctly, the contrasted supposition was discountenanced by this initial set of experiments. For if the doctrine of an absolute pitch for the resonance of every vowel be correct, it ought to be quite impossible to produce different vowels with the same pitch of resonance. A vowel whose resonance was a^4 ought to be always the same vowel. But on reference to the table of these first results *(Speech-Sounds*, § *8)* it is seen that a series of half-a-dozen distinguishable varieties of whispered vowel were developed, and yet that their upper resonance never varied a semitone either way from a^4. It could not be otherwise, because all the tubes had the same length of 44 mm., and the length of this tube or neck fixes,—subject only to slight allowances,—the pitch of the neck resonance.

To make this point clearer, a second set of experiments was made with the same apparatus, but with a different set of tubes. The length of the tubes was in this case uniformly 55 mm., and the pitch of the upper or neck resonance was consequently in this case between f^4 and $f^4\sharp$. But, notwithstanding this difference in the pitch of the resonance, the same vowels (see *Speech Sounds*, § *9*, Table II.) were again produced. When it thus appeared both that different vowels might be produced with the same upper resonance, and that the same vowel might be produced with different upper resonances, it seemed unnecessary to combat further the hypothesis of a single absolute pitch. But it is necessary perhaps, in order to add cogency to these remarks, to add that it is these same *upper* resonances which have been made the subject of observation by the advocates of that theory in order to determine their supposed absolute pitch.

This is not the only lesson, however, which was taught by Table II.; it had something to say on the organic as well as on the acoustic side of the enquiry. On comparing the tubes which yielded the best types of *i*, i^2, and the other adjacent sounds in the two sets of experiments, it became evident that they were related by a remarkable law. The tube which yielded the best type of any given vowel in the second set of experiments was, as we already know, longer in the proportion of 4 to 5 than the corresponding tube in the other set. It now came out that its *calibre* was in each case *smaller* in the inverse ratio, viz., that of 5 to 4. And seeing that the volume of the tube is the length multiplied by the calibre, the curious result was now arrived at that the quality of the whisper emitted by our experimental bottle depends on *the volume of the tube-neck* which is fitted into it.

A small qualification needs mentioning here. The length here spoken of is not the actual, but the "reduced" or effective, length of the tube; and the volume is its "reduced" volume. The "reduced" length of an open tube is found by adding $\frac{3}{5}$ of its diameter to its length. Thus the so-called "reduced" length and volume are both larger than the actual length and volume. This calculation does not hold good when the tube is very short and wide; but seeing that the vowel-tubes to which we need to apply it are always several times longer than their mean diameter, the exception is of no practical consequence: there is no need to fit tubes into our experimental apparatus which bear no resemblance to the natural tubes which are being investigated.

This singular fact having been established, the next step was to attempt its expansion into a general law. For this purpose it was evidently necessary to vary the conditions, and especially those conditions which had remained unchanged in the two first series of experiments. The principal thing was to vary the cavity into which the tubes were fitted, and in order to do this in the readiest manner, another apparatus was devised. This consisted of a short cylinder of glass, somewhat larger than the bottle hitherto employed, and open at both ends. Each end was fitted with a cork, the one immovable, the other capable of sliding up and down the cylinder in the manner of a piston. A scale attached to the side of the cylinder registered the volume of the variable cavity thus created. The fixed cork had a hole in the middle, into which a tube-neck of any desired size might be fitted. The movable cork carried the hissing-tube, which was destined to animate the resonances of the whole configuration. It was so fixed as to serve the purpose of a piston-rod at the same time: and the gutta-percha blowing-tube was fitted on the outer end of it as before.

The use of this apparatus speedily shewed, as may be seen in detail in *Speech Sounds*, § *10*, that the relation of the volume of the tube to the volume of the cavity was exceedingly simple. It was simply that for the production of a given vowel they varied in direct proportion to each other. In other words the production of any given vowel was found to be determined by the proportion existing between the volume of the cavity and the volume of the neck. When the ratio between these two was 102 the vowel made its nearest approach to *i*; when it was about 68, the vowel was the best type of i^2. But there was a slight difference observable between the two vowels, the former rising steadily to its best point and then with equal steadiness falling away, whilst the latter seemed rather better on either side of the 68 ratio, than when based exactly upon it.

These results carried with them an important though qualified confirmation of the great implied postulate of the organic system of phonetics; and they at the same time administered a further blow to the hypothesis of absolute pitch. I am not sure that the above-named postulate has ever been put into words by any of the organic phoneticians themselves, though it is the implied foundation of their whole system. It is simply that *like articulations produce like sounds.* This great truth is by no means self-evident, and stands in fact in absolute though implied contradiction to the doctrine of absolute pitch. For if half-a-dozen human beings, of identical type but widely differing size, all articulate a given vowel exactly in a given way, it is then clear that, mathematically speaking, these six examples of the configuration of that vowel will be a series of similar figures. Now if this be true, whether vowel resonance be single or double or even more complex, it is certain that the pitch of that resonance or body of resonances will vary exactly in proportion to the relative size of the configuration from which it proceeds. The pitch number of every element of the resonance will infallibly rise or fall in the exact proportion that the lineal magnitude of the configuration falls or rises.

And this is exactly what follows from the last set of experiments. For if we either increase or decrease both tube and cavity concurrently, so that the figure of the whole configuration remains always unaltered in its proportions, that constant ratio between the volume of the tube and the volume of the cavity, which is now seen to be the condition of the production of any given vowel, is exactly maintained. Similar figures do produce similar vowels, exactly as the organic system assumes. But it is also currently assumed in the same system that the converse is equally true, viz., that the same vowel always must be produced by the same articulation. This assumption is just as baseless as its converse is indisputable. Whatever measure of truth it possesses is based not at all upon acoustic necessity, but upon the organic limitations to the articulatory powers.

This possible plurality of articulations for the same vowel will be dealt with at length in my next article on *Speech-Sounds (Phonetische Studien,* IV. 3). In the meantime it may be sufficient to point out that on the principle of "tuning" already herein indicated it is impossible to alter the pitch of any uttered vowel without at the same time altering its articulation. In the vowels already studied, whose articulation aims always to produce a tube and a cavity, this tuning process is easily recognised by the rising of the larynx and the shortening of the tube, both of which changes progress steadily as we run up the scale.

The same process is even more visible in the graver vowels, though they are tuned in a totally different way. If any one standing before a mirror sings a musical scale to the vowel *o* or *u*, he will notice at once the progressive expansion of the labial orifice as he rises in the scale, shewing that here also articulation can only be constant for constant pitch.

The practical effect of this discovery is chiefly to warn us that the dicta of the organic phoneticians about articulations must be generally read as referring to the articulations of whisper and of normal monotone. Yet even within those limits there is room for a considerable play of duplicate articulations. It is true indeed that so long as the normal position of the larynx is maintained the volume of the voice-tunnel remains nearly constant, and the rules already discovered necessitate that for any given tube-vowel, a certain pretty exact proportion of this available space shall be set apart for the formation of the tube. And the tuning of this vowel to the normal monotone necessitates also, as will be shortly seen, that the length as well as the volume of this tube shall be tolerably constant. But even then there is a considerable latitude in the shaping of the tube, which is only partially limited by organic conditions. These organic limitations are least felt in the articulation of that vowel which in my other papers I have symbolized as e^2. One of the best examples of this vowel which we possess in English is the vowel of *there*. Another form of it is heard in the French *bête*. A third form may often be studied in a squalling infant. But not one of these three forms possesses a porch of the same shape, or which is formed in the same way, as that of either of the others. The organic phoneticians class e^2 as a "front" vowel, *i.e.* as having the narrowest constriction of its porch at the "front" of the tongue. But this is only true of the French vowel, for in the English one the principal constriction is formed by the upturned point of the tongue, and in the infant's cry it is easily seen that the greatest constriction is quite at the back. It is clear then that though one articulation can only produce one vowel, there may be several articulations producing a vowel which is fundamentally the same.

Returning from this digression to the strict order of the investigation, it will be seen that the natural course, after dealing with *i* and i^2, was to extend the same system of experiment, as far as it was capable of being extended, to the other vowels. This was accordingly done, and the same strict dependence of vowel-quality upon the relative volume of the tube-porch was found to extend much farther than *i* and i^2. By a gradually progressing enlargement of the relative volume of the tube-porch a sort of natural vowel-scale was created, extending from *i* to e^2 and embracing many intermediate varieties. Three things of extraordinary interest revealed themselves in this part of the enquiry. In the first place it was found, contrary to all expectation, that the first definite vowel to succeed *i* and i^2 was not *e*, but a sound strongly resembling French *u*. Further enquiry led to the more exact identification of this sound with another form of "modified *u*," which exists in Welsh and apparently also in Russian, and whose articulation is precisely intermediate between that of *i* and *e*. The reasons for the scarcity of this form of this vowel in other languages appeared to be organic (see *Speech-Sounds* § *12*). I have ventured to distinguish it by the symbol *ü*.

In the second place the *e* vowel when reached seemed to be two-fold. Notice has been already taken of the fact th the best i^2 was not realised exactly in the middle of its range, but at two points situated one on each side of the middle: and the same thing seemed to repeat itself much more strongly with *e*. There were not only two different maxima for this vowel, but in passing *gradatim* from the one to the other the definite sound of *e* was lost and its place was taken by an obscurer vowel. The one type of *e* was emitted when the tube was 27 times less than the cavity, and the other when it was 21.6 times less. At this point it was natural to remember that distinctions have been drawn by Mr. Sweet (*Hist. Eng. Sounds*, p. 3) between the two vowels of the English word *pity* and by M. Paul Passy (*Les Sons du Français*, 2nd ed.) between the vowel of *dé* and the first vowel of *maison*. These distinctions are so fine as to escape any but a keen and well-trained ear, but they fall in very remarkably with the doubleness experimentally discovered in i^2 and *e*.

The next definite vowel in the series was that which I have called e^2. This also was found to exhibit the same doubleness of type as *e* itself, but in an even more pronounced degree. Nevertheless it did not seem well to indicate these fine distinctions by a total difference of sign. I therefore called the two pairs in question *é* and *ė*, $é^2$ and $ė^2$, respectively. They can never rank in any language as consciously different vowels to the generality of speakers and hearers, but they may serve to point the difference between what are accepted as identical vowels in different languages, or even in different positions in the same language.

The third remarkable thing about this vowel series was that which was noticed at first in the isolated case of *i* and i^2 These definite types of vowel sound never shade off directly into each other. In passing by slow degrees from the one to the other we always pass through an obscurer sound,—not a mixture of both, but considerably less definite than either. It is generally extremely difficult to recognise the exact quality of these duller vowels in their feeble whispered form; and it seems better to defer their fuller consideration until they can be all compared with one other, and until perhaps some means can be devised of producing them more loudly. Meantime it may be sufficient to say that in quality they resemble, as a class, such vowels as the *eu* and final *e* in French, the *ö* and final *e* in German, the short *u* and certain vowels compounded with *r* in English. These really constitute a very large class, though their relative indefiniteness, or what is about the same thing, their relative want of interdistinguibility, prevents them from being separately and therefore numerously employed as consciously distinct elements in actual language. To my appreciation there are at least four distinct forms of the short *u* current in English; and though their difference in sound is not very great the contrast in their articulations is very much greater.

I have purposely avoided up to this point any mention of the numerous acoustic calculations and observations by which the foregoing enquiries into the shape and magnitude of vowel cavities were accompanied. It seemed better to reserve them to be viewed at one glance, so that they might lead up more directly to the general vowel-theory here announced. Having so far used acoustic means to elucidate configuration, we now turn round and use the configurations thus determined, in order to elucidate the acoustic nature of the vowels. The means of this determination were afforded partly by the formula of Sondhauss already quoted, viz.:

$$N = 46705 \frac{\sigma^{\frac{1}{2}}}{L^{\frac{1}{2}}\ S^{\frac{1}{2}}}$$

This gave the resonance of the totality: whilst the ordinary law of open tubes

$$n = \frac{V}{2L}$$

where V is the velocity of sound and L is the length of the tube, was found to express with sufficient accuracy the note of the neck. Its small deviations from accuracy are discussed in *Speech-Sounds*, § *5*.

By combining these two equations together and giving to V its mean value of 341,375 millimetres per second, we get the equation—

$$\frac{n}{N} = 3.654 \frac{S^{\frac{1}{2}}}{L^{\frac{1}{2}} \sigma^{\frac{1}{2}}}$$

But $L^{\frac{1}{2}} \sigma^{\frac{1}{2}}$ is simply the square root of the volume of the tube-neck or porch, and $S^{\frac{1}{2}}$ is in like manner the square root of the volume of the chamber or cavity; and if we now take R to symbolize the ratio of speed between the upper and lower resonances, and r to represent the ratio of volume between the cavity and the tube, the same equation may be written in the very simple form—

$$R = 3.654 \sqrt{r}$$

This expression seems to embody, for the acuter vowels at least, that fundamental relationship between configuration and sound which is the present obvious desideratum of phonetic science. Its importance is at once made manifest by the conclusions to which it leads.

The main result of the investigations already spoken of was to show that r, the ratio between the volume of the cavity and the volume of the tube or porch, is always the same for any given vowel. The formula just arrived at leads to the further conclusion that if r is constant for any given vowel, R also, the ratio between the pitch-numbers of its upper and lower resonances, will be constant too. It thus seems that, in demonstrating the essential organic constitution of these vowel configurations, the primary acoustic conditions of the same vowels have been unwittingly demonstrated at the same time. And the nature of those conditions is just what the discovery that vowel resonance was not single, but at least double, made it permissible to suspect. Vowel-quality is not conferred by the absolute pitch of one or more concomitant resonances, but by the relative pitch of two or more. In the cases hitherto examined, and probably in those of the most salient vowel types generally, vowel quality is the work of two leading resonances only.

Further consideration, however, led to a recognition of the fact that even in the skeleton configurations which were used for the foregoing experiments these two leading resonances were not the only ones which were developed. Other concomitant resonances were found to exist, and they assumed a great importance when the general theory of vowels came to be thought over. But all these minor elements possessed a certain relationship, and indeed owed all their prominence to the relationship which they possessed, to the two leading tones. It seemed well therefore to call these two the *radical* resonances of any given configuration, and to call R, the ratio of the upper to the lower, the *radical ratio* of the vowel.

Repeated experiments and calculations (see Tables I. to VIII. in *Speech-Sounds*) pointed to substantially identical values for the radical ratio of each vowel in the scale already experimentally established. The radical ratio of *i* seemed to be about 37, that of i^2 to range from above 31 to below 29, that of *ü* to be about 23, that of *e* to be 19 for its acuter form *é*, and 17 for its graver, *è*; and lastly e^2 seemed to be based upon a ratio of 13 for $é^2$ and of 11 for $è^2$. All of these figures are of course readily translatable into ordinary musical terms. A certain definite ratio between the speed of vibration of two musical tones is exactly equivalent to a certain interval of pitch between them. The ratio 37 is just equivalent to an interval of 5 octaves and 2½ semitones; the ratio 31 is equivalent to 5 octaves all but half a semitone; that of 29 is a semitone less: that of 23 is 4 octaves 6¼ semitones: 19 gives 4 octaves and 3 semitones: 17, 4 octaves and one semitone: 13, 3 octaves 8½ semitones: and 11, 3 octaves, 5½ semitones, all in just intonation.

The most striking thing at first about these results was their appearance of utter irregularity. There seemed to be in them a purposed avoidance of musical and arithmetical simplicity, which accorded ill both with *á priori* expectation and with some of the most suggestive experiments of Helmholtz upon the graver vowels. It will be sufficient to quote one short passage from Helmholtz to show how completely this was the case. "On applying to a reed-pipe which gave $b\flat$, a glass resonator tuned also to $b\flat$, I obtained the vowel *u*: changing the resonator to one tuned for $b^1\flat$, I obtained *o*: the $b^2\flat$ resonator gave a rather close *a*, and the d^3 resonator a clear *a*." (Ellis's ed. 1885, p. 117).

This is one of several passages in Helmholtz wherein the essential duality of the principal vowels seems to offer itself to observation, without, however, drawing any general inference of that kind from the investigator himself. When the above experiments are well considered they present a very close acoustic analogy to those which are herein already recorded. They testify in effect to the commixture of two tones, the one of a reed-pipe and the other of a resonator, and to the effects of that commixture in producing artificial counterparts of the graver vowels. But, in contrast to the results just summarised for the acuter vowels, the relationships disclosed by these experiments are of the simplest possible nature, whether they be considered in respect of their musical intervals or of their arithmetical ratios. The *u* vowel is produced by two tones in unison, the *o* vowel by a tone and its Octave, the imperfect *a* by an interval of two Octaves, and the clear *a* by that of two Octaves and a Major Third. Expressed arithmetically, the relation between the two co-operating resonances (or the radical ratio, as it was called for the acuter vowels) is in the first case simply 1, in the second 2, in the third 4, and in the fourth 5.

The ratio 3 was here seen to be wanting; and in order to fill up the gap, I devised an experiment which exemplified that ratio, and which yielded a vowel closely resembling the English word *awe*,—a vowel which by the older phoneticians is generally called "*open o*," and which in *Speech-Sounds* I have symbolized as o^2. But, on scrutinizing carefully this new series of five radical ratios and five corresponding vowel-sounds, a hint was obtained which seemed at last to bring under one law the whole series of cardinal vowels, acute and grave included.

It seemed extraordinary that, while the ratio 1 was associated with the *u* vowel, the ratio 2 with the *o* vowel, and the ratio 3 with the o^2 vowel, the ratio 4 was not associated with a good *a;* the good *a* was founded on the ratio 5. Wherein did 4 differ from 1, 2, 3 and 5, that it should not be equally capable of producing a marked type of vowel? There was just one thing in which it differed from them all: it was *not a prime number.* And when the results obtained for the acuter vowels were glanced at it was seen at once that here also the ratios expressed by prime numbers had yielded the best known and most definite types of vowel-sound; whilst the ratios which were not prime had all produced obscurer types of vowel. And not only were the more definite vowels thus found to be uniformly based on prime ratios, but it had almost been proved that every prime ratio, up to 37, produced a definite vowel. When the series of prime numbers 1, 2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, was written out, it was seen immediately that, with one single exception, there was a definite vowel based upon every one of them.

That exception was the number 7; and even here the cause of the exception was speedily brought to light. Helmholtz, being a German, naturally used the names of the vowels with exact reference to their German values: and an experimental reproduction of his "clear *a*" shewed that the sound which he intended to indicate by that name was that which German phoneticians distinguish as the *o* basis of *a*, a sound which I have represented in *Speech-Sounds* by the symbol a^o. There is another form of the *a* vowel which is called by way of distinction the *e* basis of *a*, to which I have ventured to apply in like manner the symbol a^e. The distinction between these two may be realized even more readily by an English than by a German ear, because both forms of *a* are familiar in English, whilst only one of them is so in German. The *o* basis of *a* is nicely represented by the English *a* in *path*: the *e* basis of *a* by the English *a* in *man*. This distinction is well heard in good public English, neither Northern nor Cockney, and best of all if the speaker has any inclination to lengthen the short vowel of *man*. In Northern speech the distinction is neither so wide nor so clear, because the usual shortness of the *man* vowel prevents it from being so keenly appreciated, whilst in Southern speech it is sometimes exaggerated so far that $\grave{e}^2$ and o^2 are heard instead of a^e and a^o. The exaggerated pronunciations here indicated will perhaps be better recognised if for once I spell them thus—*män*, *pawth*.

Seeing that a^e does not exist in German it became clearer than ever that Helmholtz's "clear *a*" was a^o; and this conclusion also left the a^e vowel free to be assigned with some probability to the vacant prime radical ratio, 7. The series being thus completed, the results were now tabulated and their relations further considered.

Vowel.	Nearest Key-word.	Nearest English Key-word.	Radical Ratio.	Stretch. Oct.	Stretch. Semit.	Difference of Stretch. Semitones.
i	French f*i*ne	f*ie*nd	37	5	2½	
						3
i^2	English p*i*t	p*i*t	31	4	11½	
						1
i^3	English pit*y*	pit*y*	29	4	10½	
						4¼
$\ddot{u}$	Welsh modified *u*	*N. Devonshire* too	23	4	6¼	
						3¼
$\acute{e}$	French d*é*	h*a*te	19	4	3	
						2
$\grave{e}$	French m*ai*son	h*a*te	17	4	1	
						4½
$\hat{e}^3$	French b*ê*te	m*e*n	13	3	8½	
						3
$\grave{e}^2$	English m*e*n	m*e*n	11	3	5½	
						7 7/10
a^e	English m*a*n	m*a*n	7	2	9 4/5	
						5 4/5
a^o	English p*a*th	p*a*th	5	2	4	
						9
o^2	English *awe*	*awe*	3	1	7	
						7
o	German l*o*hn	b*o*ne	2	1	0	
						12
u	French p*ou*le	p*oo*l	1	0	0	

Several questions naturally suggested themselves when the results were tabulated in this way. Why, for example, should 37 be the last prime ratio to afford foundation for a vowel? No reason was obvious why the series should not be produced *ad infinitum*. But actual trial with the experimental bottle shewed (see *Speech-Sounds*, Tables I. and II.) that configurations framed to realize the higher ratios failed to emit definite vowels. The sounds immediately encountered were found to resemble English consonantal *y*. The reason for this result seemed to be, partly that to realize these ratios the tube-porch had to be diminished so much as to impede the deep inner resonance from taking its indispensable share in the process of vowel formation, and partly that above 37 there are no two consecutive prime ratios which would create a difference of even two semitones in musical stretch; and the table itself seemed to shew that this is about the point where vowel distinctions cease to be appreciable to ordinary ears.

The question of relative appreciability, being thus raised, led up to several interesting observations respecting this table, mostly tending to show that there is a fair correspondence between the figures shown in the last column and the breadth or narrowness of acoustic distinction between the sounds themselves. The widest gap in the table, viz.: that between *o* and *u*, is also clearly the widest acoustically, for it is possible here, more than anywhere else in the table, to insert a vowel which shall be intermediate between the two and yet clearly distinguishable from both. The vowel of the English word *good* fulfils this condition completely. To an English ear indeed this vowel seems to deserve a place among leading types of vowel-sound. We are almost forced to think, however, that its radical ratio, when discovered, will not be, like the rest, a prime integer, but probably some very simple fraction, such as $\frac{3}{2}$. In that case it would simply divide the long interval of 12 semitones between *o* and *u* into two portions of 5 and 7 semitones respectively.

On regarding in turn the narrowest arithmetical distinctions here tabulated, it is at once seen that the smallest of all is that for whose acoustic recognition we are indebted to Mr. Sweet; and the next in point of size is that which was brought to our knowledge by M. Paul Passy. These are both insensible to ordinary and inattentive ears. It is not till the limit of 2 semitones is passed that we encounter any difference of a usable kind,—none certainly which is used in any Western European language to mark off from each other two consciously distinct vowel-sounds. But there are two differences of three semitones each in the table; and both of these are used in English to indicate important vowel-distinctions. One of these is the distinction, universal in English, between the sounds of long and short *i* (e.g. *keen* and *kin*); the other may be heard, in the exaggerated English pronunciation already referred to, in the contrasted sounds of *man* and *men*. The same people who push the vowel of *man* as far as $\grave{e}^2$ are obliged at the same time to push the vowel of *men* as far as $\acute{e}^2$ in order to preserve any kind of distinction between them. The difference in stretch between these two vowels is just three semitones.

Mr. Sweet had already noticed that the *men* vowel has a double value in English, and that one of its forms is commoner in the North, and the other in the South. He calls the former the "mid-front-wide" vowel, and the latter the "low-front-narrow." It is difficult to say whether the distinction thus observed is exactly that which is here noticed in the same vowel; but the fact that he finds the e^2 vowel to be acoustically twofold is at least noteworthy.

Turning now to the wider gaps in the series it will be seen that they are found in those places where the most striking acoustic contrasts also exist. The largest interval, 12 semitones, separates *u* from *o*: the next, 9 semitones, separates the two *o* vowels from the two *a* vowels; whilst the third, 7.7 semitones, divides the higher *a* vowel from the lowest *e*. Thus three out of the four gaps which mark off the five cardinal vowels, *u*, *o*, *a*, *e*, *i*, are indicated at once on the face of the table: and a fourth gap of similar size is created by overleaping the *ù* vowel, which both its organic and acoustic conditions seem equally to cooperate to exclude. When this is done there is a fourth gap, of 7.5 semitones in stretch, between any kind of *e* and any kind of *i*; and thus the traditional scale of five cardinal vowels is justified and carried down to an exact and scientific foundation.

The reasons which exclude *ù* from this primary scale are partly acoustic and universal, seeing that in any stage of language where five vowels only were used, the extreme and thoroughly differentiated *i* would infallibly be preferred as a fifth vowel to the less forcibly distinguished *ù*: but there may be also organic reasons which conspire either to suppress this vowel in some languages altogether, or to transform it into *ü* (the French *u*). This is a vowel of extremely similar sound, but of so widely different an articulation that it is commonly regarded as belonging to a category of vowels quite distinct from the cardinal series *i*, *e*, *a*, *o*, *u*. These "modified" *u* vowels are specially discussed in § *12* of *Speech-Sounds*, and reasons are there given for thinking that the *ù* vowel had a brief existence in Anglo-Saxon, but speedily coalesced with the *ü* vowel which already existed in that language and which is symbolized therein by the letter *y*. Neither vowel, however, has now any existence in normal English.

The only intervals in the table which remain still to be noticed are two in number and both of a middle kind. They are represented in the table by intervals of 4½ and 5⅘ semitones respectively, and they thus indicate in a suitable proportion the palpable but minor differences between *e* and e^2, the "close" and "open" *e* of the older phoneticians, and between the *e* basis of *a* and the *o* basis of *a*, as defined by contemporary German writers.

When the supposition that the most definite vowel-sounds are based upon prime ratios of resonance had thus been found to quadrate very closely with all the facts, it seemed advisable next to enquire whether there was anything either to countenance or to discountenance such a supposition on the side of theory. Would it square, in short, with the known principles of acoustic science? The way to a satisfactory reply was found to lie through a closer consideration of the minor resonances, which necessarily arise in all vowel-configurations, though in varying number and force. They are considered at considerable length in *Speech-Sounds*, § *17*.

These minor resonances are of two kinds, which may be called resultant and proportionate resonances respectively. The resultant resonances are so called because they are directly created by the two principal or radical tones. The proportionate resonances on the other hand do not spring immediately from the two principal tones, but their vibrations are favoured and magnified by their close arithmetical relationship to one or both of those tones.

The resultant tones are again divisible into two different kinds, one of which may be called differential and the other summational tones. The former are so called because their rate of vibration is the difference between the vibrational rates of the two tones which produce them: the latter, on the other hand, vibrate at the rate which is found by adding the rates of the two generating tones together. Resultant tones of both these kinds are generated whenever two musical tones are sounded simultaneously (see Helmholtz, *Sensations of Tone*, chap. 7). It hence follows that though we may speak of a resonance containing two principal tones, we can never have one which consists of two such tones only, in absolute purity. Take for example the i^3 resonance, which was found to consist mainly of two tones whose radical ratio ranged from 31 to 29. The meaning of that was that, if the radical ratio was 31, the vibrations of the porch would be 31 times as fast as those of the totality. But such a mixture would never be quite pure, because there would immediately arise a differential tone, vibrating only 30 times as fast as the fundamental, and a summational tone, vibrating 32 times as fast.

If now the radical ratio was changed to 30, the resultant tones would not be the 30th and 32nd multiples of the fundamental, but the 29th and 31st. This explains the otherwise puzzling fact that the i^2 vowel is heard not only when the configuration has either of the prime radical ratios 31 and 29, but also when its radical ratio is 30,—a number which is a very long way from being prime. For though the upper resonance itself is the 30th multiple of the fundamental, it has as its two resultant tones both of the prime multiples (29th and 31st) upon which the vowel is founded. I have given reasons (*Speech-Sounds* § *19*) why these resultant tones should be taken up and developed more vigorously in the *i* tube than in the *e* tube, which, if well founded, would fairly account for the fact that the *e* vowel fails to sustain its quality when based upon the 18 ratio, with resultant tones based upon 17 and 19; whilst the i^2 vowel is fairly sustained upon the ratio 30 by resultant tones based upon 29 and 31.

The consideration of these resultant tones seemed also to disclose the reason why the progressive changes from vowel to vowel, in the several series of experiments recorded, were not sudden, but gradual and wave-like. The definite vowels were not each suddenly realized when the appropriate ratio was reached; the quality of the vowel was increasingly felt some steps before it reached its perfection and continued to be likewise decreasingly felt for several steps after its perfection was past. This phenomenon seems fairly assignable to the nimbus of resultant adjacent tones by which the upper resonance of these acuter vowels is always necessarily accompanied. The power which nearly consonant aerial vibrations have of tuning themselves to each other renders it likely that in these upper vowels the porch always vibrates in exact multiples of the fundamental. If, for example, in the case of i^2 already instanced, the proportion of tube to cavity were further altered, so that, apart from this tendency to vibrate in exact multiples, the vibrations of the porch ought by calculation to be 29.7 times as fast as the fundamental, it seems probable that the porch would refuse to observe this fractional ratio, and would vibrate still in the exact ratio of 30; but a great change would at the same time be wrought in the resultant tones, for the tube would take up the 29th multiple much more vigorously and the 31st much less vigorously than it did before. If the configuration were then further progressively altered in the same direction, the force of the 29th multiple would continue to grow, and from that point at which theoretically the ratio of the two resonances ought to be 29.5, the two multiple tones would change places,—the 29th becoming thereafter the principal or radical resonance, and the 30th being its chief resultant tone.

The conclusions thus arrived at caused the results already tabulated to be read in a somewhat different sense. It did not now appear that when, in these acuter vowels, the radical ratio was intermediate between two integers, the porch really vibrated in a ratio which was not integral, but that it vibrated in two integral ratios simultaneously, leaning more or less strongly, however, to the nearer of the two integers. Nothing could explain better than this conclusion the gradual and wave-like change which had characterized the appearance, culmination and decline of each vowel in the progressive alteration of the radical ratio. Nor was this the only explanation which these considerations led up to. They seemed also to throw valuable light upon the causes of the felt difference in musical quality between various vowels.

The musicians' favourite vowel is a^{o}. Compared with this *o* is dull and *u* is duller: even a^{e} is rough; whilst *e* in every form grates and *i* squeals. The reasons of these distinctions are not entirely connected with the phenomena of resultant tones. They depend partly on the superior musical volume which is conferred on the a^{o} vowel by its very open articulation. But volume is not everything, as may be easily judged by a comparison with the equally open but far less pleasing a^{e} vowel. The real source of this kind of difference seems chiefly to lie in the resultant tones. It is easy to see, by glancing at the table of radical ratios, what the resultant tones in each case are, and to gain some idea of their effect upon the compound tone of which they form a part.

In the *u* vowel, as constructed by Helmholtz, with a radical ratio of 1, no differential tone is possible, and the summational tone would be the simple Octave. In the *o* vowel, with a radical ratio of 2, the differential tone would be identical with the fundamental, and the summational tone would be the Twelfth. In the o^2 vowel, radical ratio 3, the differential tone would be the Octave, and the summational tone would be the Double-Octave of the fundamental, whilst the upper or porch resonance would occupy the Fifth of the octave between them. We should expect in this case, as in that of other musical tones, that the presence of resultant tones thus related to the prime tones would greatly enhance their musical quality. The fundamental, enriched by its Octave and Double-Octave, ought to gain greatly in brilliancy and hardness; whilst the porch resonance being related to both of the same tones by very perfect harmonies ought to gain perceptibly in richness of tone. This is probably, in the final analysis, the foundation of the firm and round musical character of the o^2 vowel.

The a^o vowel is not so hard, but richer. Its radical ratio being 5, its resultant tones are 4 and 6 times as fast as the fundamental. They are, therefore, its Double-Octave and the Fifth above its Double-Octave respectively, whilst the porch resonance is itself the Third above the Double-Octave. When these are combined they simply produce the fundamental chord of the Double-Octave, backed by the deep vibrations of the totality. Such a constitution of tone is quite sufficient to account for the rich quality of the a^o vowel.

But in the a^e vowel the case is altered considerably. The radical ratio is 7, and therefore the resultant tones are 6 and 8 times faster than the fundamental. That makes them harmonic indeed to each other, but inharmonic to the intervening porch-resonance. Hence the resultant tones, instead of giving crispness and richness to the resulting vowel-sound, begin from this point to detract more and more from its musical quality. In the *e* and *i* vowels the resultant tones are not only inharmonic to the porch resonance but also to each other. The musical effect of this dissonance will perhaps be realized better when it is remembered that the difference between the porch resonance and either of its resultant tones would in the *e* vowel be less than a semitone and in the *i* vowel less than half a semitone.

These conclusions respecting the acuter vowels are exactly paralleled by Helmholtz's explanation of the musical quality of certain kinds of trumpets. The reason he assigns for their blatant and ear-shattering effect is that their prolonged conical tubes strongly favour the development of such overtones as are very high multiples of the fundamental note of the tube: and seeing that in this case, as in the other, it is impossible to arouse any such high multiple of the fundamental without also arousing in some degree the adjacent multiples also, the same kind of dissonance is aroused in these instruments as is more feebly excited in the acuter vowels. It is this which gives to those vowels that penetrating character, which, for the practical purposes of speech, makes them just as effective as the really more powerful sounds of the graver members of the series.

It is time now, however, to turn to that other great division of minor resonances previously distinguished as proportional tones. These bear much more closely upon the theory of the definiteness of prime resonances than those which have just been discussed They also, like the previous class, fall naturally into two subdivisions, of which the one consists of those which are intermediate in pitch between the two leading resonances and the other of those which are higher than both. There are none lower than both: this follows as a matter of course from the definition of the fundamental. The former of these two classes is the more important, but the latter has been already slightly touched upon, and it will therefore perhaps be better to complete the treatment of it first.

The influence of these high proportional tones was already seen in those initial experiments by which it was attempted to reproduce the (long) *i* vowel. The attempt was not fully successful until the shape of the porch had been altered from that of a cylinder to that of a dice-box or double funnel. It was then concluded, after due consideration, that the acoustic effect of this alteration had been to confer upon the porch resonance high proportional tones of its Octave and Double-Octave. The importance of these upper tones was made clear by the fact that their absence was sufficient to mar the brightness of the *i* vowel. And very similar conclusions were reached when the time came for examining the *e* vowel also (see *Speech-Sounds*, § *14*). It seemed possible to articulate and produce the so-called "narrow" or keen *e* by means of a double-funnel porch like that of normal "narrow" or keen *i*. But a prevalent form of keen *e* seemed to be actually articulated in a somewhat different way. The aim of this articulation seemed to be to produce a long single-funnel configuration, of which the narrow end was near the teeth and the wide end near the uvula. The acoustic effect of a long tapering figure like this would be to develop upper proportional tones of the Octave and Twelfth, but hardly of the Double-Octave. That would need a more gradually tapering tube. The effect of the Octave, however, would be to harden, and of the Twelfth to enrich, the tone which it accompanied. It seemed, therefore, that some very typical forms of *e* also owed their distinctiveness to their upper proportional tones. The same conclusion will be enforced in still greater variety with respect to the e^2 vowel in my forthcoming paper thereon.

But it is time to quit these upper proportional tones in order to consider that more important class which has been called intermediate proportional tones. These derive their great importance from the heterogeneous nature of the glottal noises. This heterogeneousness is palpable in the case of whisper, but not quite so evident when the glottis is in its sonant condition, especially in song. It is in fact the aim of the singer to smoothe away all noise except that one musical note, the prime tone for the time being of the vocal chords, which he is trying to sing. But it is interesting to note that the distinctness of all speech-sounds declines *pari passu* with this smoothing away of glottal noise. The comic singer, to whom distinctness of articulation is much more important than high quality of tone, generally purchases the former at the expense of the latter: and so markedly and purposely inferior is the tone of the speaking to that of the singing voice that Helmholtz has concluded that there is some essential difference in the mode in which the vocal chords are approximated in either case. He suggests that in singing they meet evenly, edge to edge; but that in speaking they overlap a little and strike each other in vibrating so as to exaggerate the frictional effects. Hence there is a large volume of glottal noise in ordinary speech as well as in whisper: and, therefore, the conclusions which are here arising from the study of the latter are not without applicability to the former also.

The result of this heterogeneity of the glottal vibrations is to confer on them, as already noticed in an earlier page, a very wide and varied power of stimulating resonance. Wide as is the interval in some of the vowels between their upper and lower resonances it is probable that the heterogeneous glottal vibrations will contain elements of nearly every grade that intervenes between them. When these are poured into the resonant voice-tunnel they will meet with a fate varying very widely, because it is essentially governed by the relationship in which they happen to stand to the two leading tones. Those which accord nearly enough with the exact tones of the porch or of the totality, or with their immediate resultant tones, will be at once bent to their respective service and forced into unison with them. Those, on the other hand, which conflict with both of the radical resonances will be damped and discouraged. Even those which have a very simple ratio to one of the radical tones, but have no such simple relation to the other, will not always be the most favoured of the intermediate resonances. There are in most cases certain classes of tones which vibrate pretty nearly at certain rates which are simultaneously multiples of the frequency of the fundamental and sub-multiples of that of the porch-resonance. It is these classes of tone which in such a case are encouraged most strongly and unified most completely by the operation of the two chief resonances.

Every resonant cavity vibrates most loudly to its own proper tone or tones. And on the other hand, it refuses to resound at all to any tones which do not chime in any way with its own. But if the vibrations which proffer themselves are related to those of the proper tone by some very simple ratio, so that, though they do not chime at every pulsation, they do so at every second or third or fourth, they are no longer disregarded by the cavity, but are taken up and resounded with a force only inferior to that of the proper tone itself. This principle applies with peculiar force to a cavity which has *two* proper resonances; for then it is sometimes possible, as just pointed out, that tones may proffer themselves which are simultaneously entitled to support from *both* of these proper resonances, and which may, therefore, succeed in eliciting a particularly loud response.

Suppose, for example, that a certain configuration possessed a radical ratio of 24, and that into this configuration was poured the usual concourse of glottal vibrations, comprising of course, among others, vibrations of every period intervening between those of the two radical resonances. Those which were hardly faster than the fundamental would be bent to the service of the fundamental: those which were nearly 24 times as fast, to the service of the porch: those which were about 23 times as fast, to that of the lower resultant tone: those 19 times as fast, however, would clash with everything except the fundamental, and would therefore be thoroughly damped. But there would be six masses of tone, composed of all those vibrations pulsating respectively about twice, or 3 times, or 4 times, or 6 times, or 8 times, or 12 times as fast as the fundamental, which would each enjoy a very notable amount of support; because they would at the same time be vibrating just 12 or 8 or 6 or 4 or 3 times or twice as fast as the porch-resonance. Each of these, being rounded and assimilated by the selective and stimulative action of the two chief resonances into a strong and compact body of tone, would naturally become an important element in the compound vowel resonance of the configuration: and their importance would be then still further enhanced by the support which they would lend to each other.

But it must always be remembered that the results just pictured can only happen in certain cases. Suppose for example that a slight alteration was introduced into this configuration, so that its radical ratio was no longer 24 but only 23. Not one of the six bodies of intermediate tone just spoken of would stand any longer in the same advantageous position. The arithmetical conditions which previously lent support to them on every side would have completely disappeared. Instead of having a strong phalanx or plexus of intermediate tones, the new vowel-resonance would approach as nearly as possible to the condition of having no intermediate tones at all. The radical ratio 23, being a prime number (*i.e.* a number which cannot be divided by any other number, except 1, without leaving a remainder) renders the existence of any intermediate tones of this doubly consonant kind impossible. For since there is no number whatever which is at the same time an exact multiple of 1 and an exact sub-multiple of 23, there cannot be in this case *any* intermediate class of vibrations, pulsating exactly a certain number of times faster than the fundamental and at the same time exactly a certain number of times slower than the porch resonance. Hence it follows that, when the radical ratio is a prime number, the most powerful (*i.e.* this doubly consonant) class of intermediate proportional resonances disappears.

Now, the conclusion reached by Helmholtz in his classical researches into the nature of the sense of hearing was that the ear discriminates all mixed modes of vibration by resolving them into their simple or pendular elements (see *Sensations of Tone*, p. 33). We hence conclude that in the hearing of a vowel there is implicated an analysis of its resonances in and by the ear, followed by a cognition of the results of this analysis. It seems fair to assume that this cognition will be readiest and keenest when the sound thus analysed by the ear is found to divide itself clearly into the fewest number of elements. The sound which, of all mixed sounds, would be most cognisable, would probably be that which, when analysed, fell into two, and only two, contrasted rates of vibration. It has already been seen that such a sound, compounded absolutely of two, and only two, elements, does not exist. But it has been shewn on the other hand that the whole of the configurations by which the chief vowels are produced bear manifest traces of being designed to emit an essentially dual resonance. And it has now been further shewn that there are strong reasons for thinking that this effort to produce a resonance as nearly dual as possible, will always succeed best when the two radical elements of the resonance are related to one another by a prime integral ratio. Putting these theoretical conclusions alongside of those which were previously realised by experiment, they seem to countenance and corroborate each other so exactly as to compel us, provisionally at least, to espouse the theory which they point to, and to make it our working hypothesis in the prosecution of the enquiries which yet remain to be made.

In the exposition and attempted proof of the above theory the primary task of this Thesis is at last accomplished. It now only remains to make a few comments and deductions with a view to illustrate its place and scope in acoustic theory, as well as in phonetic investigation. It must henceforth stand or fall according as it explains, or fails to explain, facts hereafter to be discovered. I shall myself be the most ready to discard or to amend it if it does at all fail in that respect. *Meantime I will* content myself with thinking that I may have contributed something of solid value to the methods of phonetic research as well as, incidentally at least, to its results. I hope at any rate that it may be no longer possible for professed phoneticians either to write about speech-sounds with an almost utter disregard of everything which can be learned from their organic modes of production, or on the other hand to write minutely about articulations in utter and complacent ignorance of their acoustic effects and aims.

It is worth noting that the preceding doctrines bring the analysis of vowel-timbres well into line with that of other acoustic phenomena of the same kind. It was recognised at once by Helmholtz that the differences of vowel-quality were very analogous in nature to those which are to be observed between the timbres of different musical instruments. But the nature of the vibrating body in any musical instrument is generally such that, if it emits any overtones at all, it generally emits a whole string of them: and thus it seldom happens that any instrumental tone exhibits just that duality which seems to be the characteristic of the most definite vowels. Nevertheless it is always useful to remember that the difference between vowel and vowel is just the same in kind as that which distinguishes the note of an organ-pipe from the same note on a violin; and that if we sing the same tune first to the vowel *o* and then to the vowel *a*, we create the same kind of difference in acoustic quality as if we played the tune first on a flute and then on an accordeon.

Another point worthy of notice is that the arguments by which the comparative obscurity of those vowels which are based upon ratios that are not prime was accounted for, do not apply with anything like equal force to every non-prime ratio. In that case, for example, where the radical ratio, though not itself prime, is simply the product of two prime numbers, there would not be anything like the same cloud of intermediate proportionate resonances to mar the duality of the vowel. Instead of the six strong and mutually supporting concomitant tones which were noticed in the case previously discussed, there would in this case be only two, one for each factor. If, for example, the radical ratio were 21, there would only be two intermediate tones, one being the 3rd and the other the 7th multiple of the fundamental: if it were 35, the one would be the 5th and the other the 7th multiple: and even these would not support each other. But perhaps in cases like this the least mixed, and therefore most salient and cognisable, pair of resonances would be produced when one of the factors was 2, *i.e.* when the radical ratio was just the double of some prime number. It was found, for example (see *Speech-Sounds*, Tables I. and II.), that the less definite vowel which intervenes between *i* and i^2 seemed to attain its greatest distinctiveness upon the ratio 34 ($= 2 \times 17$). The chief elements of such a resonance would probably be the 1st, 2nd, 17th, and 34th multiples of the fundamental,—the first and last in superior force. Now the effect of such a mixture would simply be to confer upon the fundamental a strong overtone of its Octave, and upon the porch-resonance a strong undertone of the same kind. Such additions could hardly be thought to cross and blur the duality of the resonance so effectually as the presence of strong intermediate vibrations of the 5th and 7th multiples would naturally do.

There is another case, however, which vies in simplicity with the one last described, and which, therefore, merits a passing notice here. It is that case wherein the two factors of the radical ratio are both the same; that is to say, where the radical ratio itself is the square of a prime number. Three such cases present themselves within the scope of this enquiry, viz: those in which the radical ratios are 4, 9, and 25 respectively. The three corresponding pairs of factors are 2 and 2, 3 and 3, 5 and 5. In these three cases it will only be possible to develope *one* intermediate tone, because both the factors are in each case identical: the only possible intermediate tones are the 2nd, 3rd, and 5th multiples, each in its several vowel. Such being the simplicity of these three resonances I hesitate as yet to assign a place to the less definite vowel which was found to intervene between i^3 and *u̇*. It reaches its clearest form when the radical ratio is about 25 or 26 (see *Speech-Sounds*, Tables I., II., and III.): but whether it is to be definitely assigned to either or both of those ratios can only be decided when these vowels of the second order are investigated more closely.

It seems unlikely that, among the the acuter vowels at any rate, a vowel of the second order can base itself upon the ratio next adjacent to that of a vowel of the first order. Thus, while the ratio 34 (2 × 17) is the basis of a satisfactory vowel of the second rank, the ratio 22 (2 × 11) fails to produce one: it seems rather to produce a bad *u̇*. The reason of this may be that the upper resultant tone of the latter of these two tone-mixtures will of course be the 23rd multiple of the fundamental, and will therefore naturally lend to it a poor resemblance to the definite *u̇* vowel. However this may be, it is clear that the theory hereinbefore developed respecting the constitution of the vowels of the first order will be an invaluable help to the investigation of those of the second order also.

But there are also vowels of a third order, possessing a great importance in some languages, though they have not yet even been named in this Thesis. These are the nasalized vowels of which American English furnishes many mild, and the French language a few strong, examples. From an articulatory point of view they are generally described as identical with the corresponding unnasalized vowels, except that the inner entrance to the nose is in their case closed imperfectly. The acoustic result of this is that a portion of the vibrating air escapes through the nose instead of through the mouth. This portion of air is animated of course by the same fundamental resonance as that which issues from the mouth, but it altogether escapes the operation of the porch resonance; or, to speak more correctly, its porch is the nasal passage or cavity, and when it reaches the outer air it is impressed with an upper resonance due to the length and other dimensions of that part of the organism. But the resonance of this cavity differs widely from that of the various oral porches in that it is almost unalterable. Instead of being endowed with the endless mobility of the oral cavity it can only be altered very slightly in two places, both situated towards its inner end. It may be altered a very little in length by raising or dropping the soft palate and uvula: and it may be closed or opened, more or less widely, at its inner orifice, behind the soft palate. Neither of these movements has any great power to alter the resonantal pitch of the passage.

These vowels, then, of the third order, differ from the corresponding vowels of the first order in being, not of dual, but of treble, resonance: and they differ from any vowels of the second order, in that the third resonance is not determined in any manner by the other two, but simply by the length and size of the nasal passage. The other resonances, whatever they may be, seem to be crossed at random by this nearly fixed nasal tone: and the acoustic impressions received from nasal vowels seem to correspond closely with this explanation. Nasality, however, is a matter of degree, and varies widely in different cases. Its force is chiefly regulated at the inner orifice of the nasal cavity, by opening it more or less widely. It is therefore possible to nasalize in some degree every vowel: but it is not possible to give the nasal resonance any very great power except in the middle members of the series, from a^{e} to o^{2} or *o*. The former is the general character of the American, and the latter of the French nasality. The continual presence of the nearly fixed nasal resonance gives to the former kind of speech a character of droning monotony: but in the latter language the violent crossing of the oral and nasal porch resonances in these middle types of nasal vowel gives to them a snarling incisiveness, not dissimilar, in its acoustic foundations, to the keener and smoother incisiveness of the vowels *i* and *e*.

And here, as in so many parts of this investigation, reflected light is thrown by acoustic explanations upon organic conditions, as well as *vice versâ*. The theory here advocated shews that the production of any acute vowel postulates the creation of a tube-porch or outlet of a definite relative volume. When this is duly carried out, the right radical ratio is determined and the vowel is duly given forth. But it is evident that if another orifice is opened and an additional tube is connected with the configuration, none of the calculations hitherto relied upon will any longer hold good. It might as well be imagined that the existing tube could be indefinitely widened without altering the conditions of the inner resonance, as that a second tube could be opened close alongside of it without equally doing so. The current assumption, then, that the articulation of a given nasal vowel is identical with that of the corresponding oral vowel, except as to the opening of the inner nasal orifice, is manifestly incorrect. The opening of that orifice, during the production of an oral vowel, would certainly introduce nasal tone, but it would at the same time upset the radical ratio which is the basis of the oral vowel. A modification of the oral articulation would simultaneously be needed; otherwise the *corresponding* nasal vowel would not be produced.

When I speak of the *corresponding* nasal vowel I do not of course refer to French or any other spelling, but to the vowel which acoustically differs only from a given oral vowel in being crossed by nasal tone. The French *in* for example is the corresponding nasal to the vowel of English *man*,—a vowel which, singular to say, is unknown in its oral form to the French language. Acoustically speaking French *main* is simply English *man*, deprived of its *n* and then strongly nasalized: the latter vowel is a^e, the former is $\tilde{a}^e$, where the sign above the *a* is intended to signify nasalization. Both vowels are essentially founded on the radical ratio 7, but the French vowel is crossed by a powerful nasal tone, which differs somewhat in pitch from the oral porch resonance, and therefore jars with it, and perhaps also with the fundamental.

The organic relation of the two vowels is, as we have seen, not quite so simple. The opening of the nasal passage is equivalent, in its effect upon the fundamental resonance, to an enlargement of the oral porch itself. The direction of this effect is readily conjectured from the formula which was borrowed at the outset from Sondhauss; it means a rise in the pitch of the fundamental resonance. On the principle of "tuning" it is necessary, in continuous whisper or normal monotone, that this alteration should be redressed. This can only be done by compensatory reduction in the dimensions of the tube. But by the same principle of tuning, the length of the tube cannot be reduced. Compensation must, therefore, be sought at the expense of its calibre. And the facts quite accord with these reasonings. Every tube-vowel without exception, when it is nasalized, not only has the nasal passage opened, but is subjected to a compensatory squeezing or narrowing of its oral tube-porch. I do not know that this fact has ever been noticed by any phonetician previously, but it is palpable to any careful observer.

The effects of this compensation are naturally more visible in the small porches of *i* and i^3 than in that of a^e. The compensation required makes a much greater inroad upon the former than upon the latter. There is in fact a great difficulty in producing a nasalized *i* at all, for its tube is reduced to such a narrowness by the necessities of compensation that the porch resonance is almost lost. It has a great tendency too to slide into a nasal i^3: nor can a really powerful nasal vowel be produced except at a still lower place in the series. Similar observations may be made at the graver end of the series also. If the observer, standing before a mirror, first sounds an *u* vowel and then suddenly nasalizes it, taking care, however, at the same time also to redress the articulation by ear, so that the sound shall be still *u*, though nasal, he will see that the labial orifice is in like manner compelled to undergo so great a compensatory reduction that here also the vowel is in danger of being smothered, just as *i* was before.

These considerations no doubt explain the history of the sounds of Latin *in* and *un* as final syllables in the French language. The growth of nasality in the vowel rendered the vowel itself impossible: for increased nasality means a wider opening of the inner nasal orifice, and that in turn means increased compensation, so that in obtaining strong nasality each of these two vowels was compelled to slide some distance towards the middle or lower middle of the series. The sound of *en* did the same thing; and so did those *an* and *on*, though in a slighter degree. Hence the marked medial quality of the French nasal vowels.

I do not offer these remarks as a complete or satisfactory treatment of the nasal vowels generally, but merely to shew that the methods herein more particularly applied to the acuter vowels of the first order, are capable of equally efficient application throughout the whole vowel field. I will now conclude this paper by directing attention to some results arrived at in *Speech-Sounds*, § *16*, as a further illustration of the fruitfulness of a conjoint use of organic and acoustic methods in phonetic investigation.

Concurrently with the enquiries into the essential nature of the acuter vowels careful observations had been made of the specific dimensions and pitch of their respective tube-porches in my own whispered vowels. When the first five vowels, *i*, i^2, *u̇*, *é* and *è*, had been completed, a table was made in which all these particulars were set forth, and the fundamental resonance of each vowel was also arrived at by calculation. It turned out that the fundamental resonance was the same, within a semitone, for all the five vowels. This was a surprise, for the incomplete statements of both Helmholtz and Bell on the same subject had aroused the expectation that these deeper resonances would form a series rising in pitch from the *i* to the *è* vowel. Moreover, the one common fundamental pitch thus discovered was B♭, just the pitch of